Method for Initialization and Stepsize Control of Time-Domain Equalizer in Multi-carrier Communication System

Background of the Invention

(a). Field of the Invention

The present invention relates in general to a multi-carrier communication system, and more particularly to a method for initiation and stepsize control of a time-domain equalizer in a multi-carrier communication system.

(b). Description of the Prior Arts

Multi-carrier modulation is widely used in communication systems nowadays. Fig.1 is a block diagram of a communication system 100 using multi-carrier modulation. The communication system 100 employs a set of N-point Inverse Fast Fourier Transform (IFFT) 102 in the transmitter and the Fast Fourier Transform (FFT) 111 in the receiver to transceive data. A channel 106 is divided into N subchannels for transmitting data. The signal transmitted by one subchannel is orthogonal to those transmitted by any other subchannels. Thus, the signal transmitted by the subchannels would not interfere each other, and inter-channel interference (ICI) can be avoided.

The set of N-point data outputted from IFFT 102 is called a symbol. Since the channel impulse response (CIR) is not ideal, that is, the amplitude/frequency response of the channel are not constant across the all used subchannels, then the received signals will different from the transmitted signal, and the signals presented to the QAM decoder 113 will different from the signals outputted from the QAM encoder 101. If the distortion is severe then the data transmitted by one subchannel will affect both the data transmitted by other subchannels (ICI) and the data transmitted by that subchannel in the previous and subsequent symbol periods (inter-symbol interference, ISI). In order to avoid inter-symbol interference (ISI) and ICI, a "cyclic prefix"(CP) is added to each symbol, i.e. the last υ points of each symbol are copied and added in the front of the symbol, as

shown in Fig.2. Therefore, each symbol outputted from adding cyclic prefix circuit 103 includes (N+υ) points. The adding cyclic prefix circuit 103 in the transmitter and the removing cyclic prefix circuit 110 in the receiver of Fig.1 are used to add and remove cyclic prefixes respectively.

In the communication system 100 of Fig.1, if the valid length of channel impulse response (CIR, denoted by h[n]) is shorter than the length of cyclic prefix, then a symbol, after being transmitted in the channel 106 and received by the receiver (i.e. the convolution of the symbol and the CIR, h[n]), would not affect the data of the subsequent symbol received in the subsequent symbol period. However, if the length of CIR is larger than that of the cyclic prefix, then ICI and ISI will occur. Under this circumstance, a time-domain equalizer (TEQ) with an impulse response w[n] ,as shown in the block 108 of Fig.1, is necessary for the receiver of the system 100. The TEQ 108 is used to modify the CIR of the communication system 100, such that valid length of the modified CIR (called target impulse response and denoted by b[n]), i.e. the convolution of the CIR h[n] and the TEQ impulse response w[n], is shorter than that of the cyclic prefix, thereby preventing the received data from ICI and ISI.

Since the CIR is different with various transmission channels, the TEQ impulse response needs to be adjusted accordingly. Many adaptive TEQ algorithms are developed in succession. Since these adaptive TEQ algorithms are sensitive to initial values of TEQ impulse response W[n] and target impulse response B[n] in frequency-domain (In the following description, time-domain variables will be referred to by lower-case letters and frequency-domain variables will be referred to by capital letters), the adapting result would be unreliable if the initial values are not properly determined during the TEQ initialization process. The adapting result will fail into the local maxima point.

U.S. Pat. No. 5,285,474 and 6,396,886 disclosed the conventional adaptive TEQ algorithms. However, both of these two patents failed to disclose the method to determine the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n]. In addition, the coefficient (called stepsize coefficient in this specification) used to stepwise adjust W[n] using frequency-domain Least Mean Square (LMS) will greatly affect the performance of the adaptive TEQ algorithms. If the

stepsize coefficient is set too small, the converging speed will be too slow; if too large, then a diverging result will occur frequently. Both cases would degrade the system performance seriously.

Summary of the Invention

In view of the above-description, it is one of the objects of the present invention to provide a method for initializing and stepsize controlling a time-domain equalizer (TEQ) for use in a multi-carrier communication system to upgrade the performance of the TEQ performing the adaptive TEQ algorithms.

According to the object of the present invention disclosed above, one of the embodiment of the present invention discloses a method for initializing a time-domain equalizer (TEQ) comprised in a receiver of a multi-carrier communication system, the method comprising: estimating a channel impulse response (CIR) h[n] according to a received symbol, wherein the received symbol includes a cyclic prefix with v points and a data portion with N points, wherein i=0~N-1; selecting one of a plurality of groups according to the total energy of the groups, wherein each group includes consecutive v points of the received symbol; modifying the channel impulse response (CIR) h[n] according to the selected group to generate a modified channel impulse response h'[n]; generating a target impulse response b[n] according to the modified channel impulse response h'[n] and a window mask m[n], wherein i=0~N-1; transforming the channel impulse response (CIR) h[n] and the target impulse response b[n] to a frequency-domain to generate a frequency-domain channel impulse response H(i) and a frequency-domain target impulse response B(i) respectively, wherein i=0~N-1; and generating a frequency-domain impulse response W(i) of the time-domain equalizer according to the frequency-domain channel impulse response H(i) and the frequency-domain target impulse response B(i). The frequency-domain target impulse response B(i) and the frequency-domain TEQ impulse response W(i) are for initializing the TEQ.

Another embodiment of the present invention discloses a method for initializing a time-domain equalizer (TEQ) comprised in a receiver of a multi-carrier communication system, the method comprising: estimating a channel impulse response (CIR) h[n] according to a received symbol, wherein the received symbol includes a cyclic prefix with v points and a data portion with N points, wherein i=0~N-1; selecting one of a plurality of groups according to the total energy of the groups, wherein each group includes consecutive v-lw points of the received symbol, wherein lw is the length of the TEQ impulse response; modifying the channel impulse response (CIR) h[n] according to the selected group to generate a modified channel impulse response h'[n]; determining a frequency-domain impulse response W(i) according to a frequency-domain modified channel impulse response H'(i), wherein i=0~N-1; and determining a frequency-domain target impulse response B(i) according to the frequency-domain impulse response W(i) and a frequency-domain CIR H(i), wherein i=0~N-1. The frequency-domain target impulse response B(i) and the frequency-domain TEQ impulse response W(i) are for initializing the TEQ.

Still another embodiment of the present invention discloses a method for adapting a time-domain equalizer (TEQ) comprised in a receiver of a multi-carrier communication system, the method comprising: determining a frequency-domain TEQ impulse response $W_k(i)$ and a frequency-domain target impulse response Bk(i) for initializing the TEQ, wherein i=0~N-1; generating a modified TEQ impulse response $w_{k,w}(i)$ and a modified target impulse response $b_{k,w}(i)$ according to a time-domain TEQ impulse response wk(i) and a time-domain target impulse response $b_k(i)$; determining a error term $E_k(i)$ according to the modified TEQ impulse response $w_{k,w}(i)$, a modified target impulse response $b_{k,w}(i)$, and a frequency-domain channel impulse response (CIR) H(i) ; adjusting the frequency-domain TEQ impulse response $W_k(i)$ to generate a adjusted frequency-domain TEQ impulse response $W_{k+1}(i)$ through performing a least mean square (LMS) operation according to the error term $E_k(i)$, a frequency-domain modified TEQ impulse response $W_{k,w}(i)$, a frequency-domain channel impulse response (CIR) H(i), and a stepsize coefficient μ, wherein the stepsize coefficient μ in a time-varying coefficient; generating a modified adjusted frequency-domain TEQ impulse response $W_{k+1,w}(i)$ according to the adjusted frequency-domain TEQ impulse response $W_{k+1}(i)$; and adjusting the

frequency-domain target impulse response $B_k(i)$ to generate a adjusted frequency-domain target impulse response $B_{k+1}(i)$ according to the modified adjusted frequency-domain TEQ impulse response $W_{k+1,w}(i)$ and the frequency-domain channel impulse response (CIR) H(i).

These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the embodiments that is illustrated in the various figures and drawings.

Brief Description of the Drawings

Fig.1 is a block diagram of a communication system using multi-carrier modulation.

Fig.2 is a diagram showing the formation of a cyclic prefix.

Fig.3 is a flow chart of the method for determining the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n] according to the first embodiment of the present invention.

Fig.4A and 4B are diagrams showing two examples of the time-domain window mask.

Fig.5 is a flow chart of the method for determining the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n] according to the second embodiment of the present invention.

Fig.6 is a flow chart of a typical adaptive TEQ algorithm.

Fig.7 is a diagram showing an example of the function f(k) used to determine the stepsize coefficient function according to the embodiment of the present invention.

Detailed Description of the Embodiments

Fig. 3 is a flow chart of the method for determining the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n] according to the first embodiment of the present invention. As mentioned above, the TEQ 108 is used to shorten channel impulse response (CIR) of the multi-carrier communication system 100. The CIR is represented by a N-point sequence h[n], n=0~N-1. The communication system 100 encodes data as symbols for transceiving, wherein each symbol comprises N sampling points and a cyclic prefix with ν sampling points.

As shown in Fig.3, the first embodiment for determining the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n], which is called the Time-domain Window Mask method in the specification, includes steps of:

30 producing an estimated CIR h[n] according to the received symbols which are known by both of the receiver and the transmitter;

31 calculating the total energy of each group of consecutive ν points and selecting the group of consecutive ν points with the maximum energy;

32 setting all the remaining points outside the selected group to zero to generate a modified estimated CIR h[n];

33 multiplying the modified estimated CIR h[n] with a time-domain window mask m[n] to generate an estimated target impulse response b[n], wherein b[n]=h[n] • m[n], n=0~N-1;

34 transforming h[n] and b[n] into the frequency domain to generate H(i) and B(i) respectively, i=0~N-1, wherein B(i) is determined to be the initial value of the frequency-domain target impulse response; and

35 determining W(i) by dividing B(i) by H(i), i=0~N-1, wherein W(i) is determined to be the initial value of the frequency-domain TEQ impulse response.

The procedure of step 31 that the ν consecutive points with the highest total energy are found by a cyclic search through N points of h[n], that is, $\sum_{n=k}^{k+\nu}|h[n]|^2$, k=0~N-1, is called the Locate Maximum Energy algorithm. The number of consecutive points of h[n] to perform the Locate Maximum Energy algorithm is determined such that the valid length of the estimated target impulse response b[n] is shorter than that of the cyclic prefix (having ν points). In this embodiment, it is ν consecutive points of h[n] with the highest total energy to be found through performing the Locate Maximum Energy algorithm. However, the value ν is not the limitation of the present invention.

In the step 33, if the points of h[k] ~ h[k+ ν -1] are selected, the points of m[k] ~ m[k+ ν -1] of the time-domain window mask m[n] are set to be the value between zero and one and the other points of m[n] are set to be zero to further modify the modified estimated CIR h[n].

Since the difference between the boundary points of the selected group and the points outside and adjacent to the selected group (set to be zero) may be too large in value, the purpose of the time-domain window mask m[n] is to further modify the modified estimated CIR h[n] to reduce the difference of value between the boundary points of the selected group and the points outside and adjacent to the selected group. Thus, the determined initial value of the frequency domain TEQ impulse response will be more appropriate. In addition, in order to shorten the CIR h[n] by stepwise adapting the TEQ 108, the value of the "tail" (the last few points) of the generated target impulse response b[n] should be decreased gradually. In this manner, it is reasonable that the initial value of b[n] should have the similar property that the value of the "tail" of the initial b[n] should be decreased gradually. The purpose of the time-domain window mask m[n] is to further modify the modified estimated CIP h[n] not only to reduce the difference of value between the boundary points of the selected group and the points outside and adjacent to the selected group but to further modify the modified estimated CIP h[n]

such that the value of the "tail" of the initial b[n] is decreased gradually. Fig.4A and 4B show two examples of the time-domain window mask m[n], which can be mathematically represented by

$$m[n]=\begin{cases} 1; k \le n \le i \\ \dfrac{(k+\upsilon-1)-n}{(k+\upsilon-1)-i}; i < n \le (k+\upsilon-1) \\ 0; others \end{cases}$$ (Fig.4A) and

$$m[n]=\begin{cases} \dfrac{n-k}{i-k}; k \le n \le i \\ \dfrac{(k+\upsilon-1)-n}{(k+\upsilon-1)-i}; i < n \le (k+\upsilon-1) \\ 0; others \end{cases}$$ (Fig.4B),

where i is an integer between k and k+ ν -1.

It is emphasized here that the "shape" of the time-domain window mask is subject to modification according to system requirements and not limited to the examples of Fig.4A and 4B.

In the step 34, h[n] and b[n] are transformed to the frequency domain by Fast Fourier Transform (FFT), which are represented by H(i) and B(i) respectively.

B(i) determined in step 34 and W(i) determined in the steps 35 are the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n], which can be applied in various adaptive TEQ algorithms.

Fig.5 is a flow chart of the method for determining the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n] according to the second embodiment of the present invention. The method includes steps of:

50 producing an estimated CIR h[n] according to the received symbols which are known by both of the receiver and the transmitter;

51 calculating the total energy of each group of consecutive ν -l_w points and selecting the group of consecutive ν -l_w points with the

maximum energy, wherein l_w is the length of the TEQ impulse response;

52 removing the group of consecutive $\nu - l_w$ points with the maximum energy from h[n], combining the remaining $N - \nu + l_w$ points, and padding zero to the last $\nu - l_w$ points of h[n] to produce a new N-point sequence h'[n];

53 transforming h'[n] into frequency domain to generate H'(i), i=0~N-1;

54 determining W(i) which is the reciprocal of H'(i), i=0~N-1, wherein W(i) is the initial value of the frequency-domain TEQ impulse response; and

55 transforming the original estimated CIR h[n] into frequency domain to generate H(i), and determining B(i) by multiplying W(i) with H(i), wherein i=0~N-1, and B(i) is the initial value of the frequency-domain target impulse response.

Based on the method disclosed in this embodiment, the w[n] (i.e. the impulse response of the TEQ 108) is determined such that the convolution of w[n] and the new N-point sequence h'[n] generated in the step 52 is an ideal impulse response. In this manner, the valid length of the target impulse response b[n], which is generated by the convolution of the w[n] and the original h[n], will be shorter. Thus, the target impulse response b[n] determined by the method disclosed in this embodiment will be more appropriate that the valid length of the target impulse response will be equal to or shorter than that of the cyclic prefix, i.e. ν points.

In the step 51, the Locate maximum energy algorithm is performed. In the step 52, the group of consecutive $\nu - l_w$ points having the maximum energy are removed from h[n], the remaining points of h[n] are combined, and the last consecutive $\nu - l_w$ points are set to be zero to generate a new

N-points sequence h'[n]. In the step 53, h'[n] is transformed into frequency domain by FFT, and H'(i) represents the FFT result of h'[n]. The W(i) and B(i) determined in the steps 54 and 55 respectively are the initial values of frequency-domain TEQ impulse response W[n] and target impulse response B[n], which can be applied in various adaptive TEQ algorithms.

Fig.6 is a flow chart of a typical adaptive algorithm of the TEQ 108. As shown in Fig.6, the algorithm is performed in an iterative way to adapt the TEQ 108 to in order to shorten the CIR of the communication system. The algorithm includes steps of:

60 determining initial value of frequency-domain TEQ impulse response $W_k[i]$ and target impulse response $B_k[i]$, wherein i=0~N-1 ,and k is the adapting index representing k-th iterative operation;

61 performing IFFT on $W_k[i]$ and $B_k[i]$ to generate $w_k[i]$ and $b_k[i]$ respectively. Then calculating the total energy of each group of consecutive l_w points of $w_k[i]$ and selecting the group of consecutive l_w points with the maximum energy, wherein l_w is the length of the TEQ impulse response, and setting all the remaining points outside the selected group to zero to generate a modified time-domain TEQ impulse response $w_{k,w}[i]$. In the same time, calculating the total energy of each group of consecutive ν points of $b_k[i]$ and selecting the group of consecutive ν points with the maximum energy, and setting all the remaining points outside the selected group to zero to generate a modified time-domain target impulse response $b_{k,w}[i]$. Then performing FFT on $w_{k,w}[i]$ and $b_{k,w}[i]$ to generate $W_{k,w}(i)$ and $B_{k,w}(i)$ in frequency-domain, wherein i=0~N-1;

62 performing $E_k(i)= B_{k,w}(i)- W_{k,w}(i) \cdot H(i)$, i=0~N-1, wherein H(i) is the frequency-domain of h[n];

63 performing $W_{k+1}(i)= W_{k,w}(i)+\mu E_k(i) \cdot H^*(i)$, i=0~N-1, to adjust the value of the frequency-domain TEQ impulse response, wherein

$H^*(i)$ is the complex conjugate of $H(i)$ and μ is a stepsize coefficient;

64 performing IFFT on $W_{k+1}[i]$ to generate $w_{k+1}[i]$, then calculating the total energy of each group of consecutive l_w points of $w_{k+1}[i]$ and selecting the group of consecutive l_w points with the maximum energy, wherein l_w is the length of the TEQ impulse response, and setting all the remaining points outside the selected group to zero to generate a modified time-domain TEQ impulse response $w_{k+1,w}[i]$. Then performing FFT on $w_{k+1,w}[i]$ to generate $W_{k+1,w}(i)$;

65 performing $B_{k+1}(i)=W_{k+1,w}(i) \cdot H(i)$ to adjust the value of the frequency-domain target impulse response; and

66 repeating the steps 61 to 65 until a predetermined converging condition is satisfied.

In the step 60, it should be noted that the method to determine the initial values of frequency-domain TEQ impulse response $W_k[i]$ and target impulse response $B_k[i]$ is not limited to the methods disclosed in this specification.

In the step 62, $E_k(i)$ can be regarded to be the error term generated by the adapting process.

In the step 63, the equation $W_{k+1}(i)= W_{k,w}(i)+\mu E_k(i) \cdot H^*(i)$ is the least-mean-square (LMS) algorithm. μ is the stepsize coefficient of the LMS algorithm. The value of μ may affect the performance of the LMS algorithm. If μ is too large, the LMS operation may easily lead to divergence. If μ is too small, the LMS operation may lead to bad local maxima and the speed of convergence will be too slow.

Based on the result of simulation, the value of μ is substantially in

proportion to the reciprocal of the power of H[i]. This condition may be shown by the following equation: μ = const / power(H[i]), wherein the value of const can be determined based on the result of simulation. It should be noted that divergence always occurs at an early stage of the adapting process if μ is too large.

In a conventional approach, μ is a time-invariant constant generated by experiments or simulations. However, in the embodiment of the present invention, μ is a time-variant function μ(k) throughout the adaptive process. Two methods for determining and controlling the value of the stepsize coefficient function μ(k) throughout the adapting process are disclosed in the specification.

The first method is called the power-ratio method in the specification, the method can be represented by the following equation:

$$\mu(k) = \frac{const}{power(H)} \times \log \frac{power(Wk)}{power(Wk - Wk - 1)}$$

Based on the above equation, μ(k) will become large if power(Wk) is increasing and vise versa. The log function is used because the value of ${power(Wk)}/{power(Wk - Wk - 1)}$ increases exponentially during the adaptive process. If (W_k-W_{k-1}) is large, ${power(Wk)}/{power(Wk - Wk - 1)}$ will decrease such that divergence can be prevented. If (W_k-W_{k-1}) is small, ${power(Wk)}/{power(Wk - Wk - 1)}$ will increase such that speed of convergence can be speeded up. According to the result of simulation, the value of μ(k) will increase gradually in the early stage of the adaptive process, and then approach to a constant in the late stage of the adaptive process.

The second method is called the fitting curve method in the

specification. Through simulation, it is known that the value of μ (k) should keep small in the early stage of the adaptive process and then the value of μ (k) should become large in the late stage of the adaptive process. It can be accomplished by setting a predetermined fitting curve function. An example of stepsize coefficient function μ (k) is provided below, as shown in Fig.7:

$$\mu(k) = \frac{const}{power(H)} \times f(k)$$

,wherein f(k)=k/M , when k<=M

=1 , when k>M

where k is the adapting index representing k-th iterative operation, and M is an integer which is preferably to be between 10 and 20.

In the above example, μ (k) is kept small in the early stage of the adapting process (i.e. k<M), while in the late stage of the adaptive process (k>M), μ (k) is kept to be a large constant to prevent from converging too slow. It should be noted that the above example function is one of the embodiments and may not be the limitation of the present invention.

In the step 65, the equation $B_{k+1}(i)=W_{k+1,w}(i) \cdot H(i)$ is called the zero-forcing criterion. The converging condition is not clearly determined in the step 66. Typically, the converging condition is predetermined to be that either the error E_k smaller than a predetermined threshold or performing the steps 61 ~ 65 for a predetermined period of time.

While the present invention has been shown and described with reference to two preferred embodiments thereof, and in terms of the illustrative drawings, it should be not considered as limited thereby. Various possible modification, omission, and alterations could be conceived of by one skilled in the art to the form and the content of any particular embodiment, without departing from the scope and the spirit of the present invention.